

# AN InGaAs-GaAs-AlGaAs LATERALLY-COUPLED DISTRIBUTED FEEDBACK (LC-DFB) RIDGE LASER DIODE

R.D. Martin, S. Forouhar, S. Keo, R.J. Lang, R.G. Hunsperger, R.C. Tiberio, and P.F. Chapman.

## Abstract:

Results are presented on laterally-coupled distributed feedback (LC-DFB) ridge laser diodes. The epitaxial regrowth required in most distributed feedback devices is eliminated by using lateral evanescent coupling of the field to gratings etched along the sides of the ridge. A pulsed single-mode output power of 36 mW per facet was achieved at 937.5 nm with a sidemode suppression ratio (SMSR) of 30 dB for a 1.5 mm cavity. A pulsed threshold of 11 mA, slope efficiency of 0.46 mW/mA per facet, and temperature sensitivity of  $0.63 \text{ \AA}/^\circ\text{C}$  were measured for a 250  $\mu\text{m}$  cavity LC-DFB.

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*Introduction:* Stable single-mode distributed feedback (DFB) laser sources are important in many applications including spectroscopy, pump sources for amplifiers and solid-state lasers, and use in coherent communication systems. DFBs achieve wavelength selectivity through feedback from a periodic change in index or gain along the cavity. This usually requires an interrupted growth - i.e. regrowth over a grating structure - in the fabrication, which is time consuming and can introduce defects at the grating/regrowth interface. Determining the proper surface preparation and growth parameters to achieve high quality epitaxial regrowth while preserving the grating structure is technically demanding - particularly for short wavelength devices with high Al content and long wavelength GaSb based devices. One way to eliminate the regrowth problem is to etch the gratings after the lasing cavity has been fabricated and rely on the coupling of the evanescent electromagnetic fields. This has been demonstrated by etching the gratings directly above the waveguide and injecting the current from the side [1] or by etching gratings through the cap and upper cladding layer to provide the index guiding for the 'ridge' and selective feedback [2 - 3]. An alternative approach is to etch the ridge first and then define the gratings on either side of the ridge (Fig. 1a) by either e-beam [4] or x-ray [5] lithography. Some other published devices [6 - 7] have also relied on evanescent feedback but required a regrowth step. In this Letter lasing characteristics of a laterally-coupled distributed feedback (LC-DFB) ridge laser using a single growth step will be presented.

*Fabrication:* The LC-DFBS were fabricated from an InGaAs-GaAs-AlGaAs graded index separate confinement heterostructure (GRINSCH)[ 8]. After the MBE growth, a piece of the wafer was processed into 100  $\mu\text{m}$  wide broad area lasers. From these a threshold current density of 145  $\text{A}/\text{cm}^2$  and a lasing wavelength of 932 nm were measured for a 1 mm cavity. The internal loss and quantum efficiency of the structure were 6.5  $\text{cm}^{-1}$  and 96% respectively.

The fabrication of LC-DFB ridge lasers is very similar to that of standard ridge devices. Photolithography was used to form 2  $\mu\text{m}$  wide photoresist stripes. A narrow ridge was used to maximize the coupling of the evanescent field to the grating. Chemically assisted ion beam etching (CAIBE) using chlorine gas in conjunction with an argon ion beam was used to etch the ridges to within 0.1  $\mu\text{m}$  of the GRINSCH. The 2 dimensional (transverse and lateral) overlap of the field to the gratings - and hence the coupling coefficient,  $\kappa$  - is critically dependent on the ridge etch depth. Etching the ridge deeper results in more index guiding of the field and reduces the lateral fill factor of the grating. Too shallow of a ridge depth reduces the transverse overlap of the field with the grating. After etching the ridge, PMMA was applied to the wafer and first order gratings were exposed (Fig. 1 b) using electron beam lithography. To avoid having to align the e-beam pattern to each side of the ridge, the gratings were written continuously across the structure. CAIBE was then used to transfer the gratings approximately 700 Å deep into the upper cladding layer. The gratings were also etched partially into the highly doped cap region. Ridges without gratings were included to allow comparison of standard devices with DFBs from the same material. After stripping the PMMA from the wafer, a self-aligned technique using silicon nitride and polyimide was used to planarize the wafer and facilitate contacting the narrow ridge. The wafer was then thinned and finished with Cr/Au (top, p-type) and AuGe/Ni/Au (back, ohmic n-type) contacts. Subsequently, the wafer was cleaved into bars of different cavity length for testing.

*Measurements and Analysis:* All results presented are for devices with as-cleaved facets under pulsed (5  $\mu\text{sec}$  pulse width at 1 kHz repetition rate) conditions. Light-current and spectral

characteristics of 250  $\mu\text{m}$  and 1.5 mm long cavity LC-DFBS are shown in figure 2. The 250  $\mu\text{m}$  long device had 1400  $\text{\AA}$  pitched gratings yielding a room temperature DFB wavelength of 921.7 nm. A threshold current of 11 mA, slope efficiency of 0.46 mW/mA per facet, and single mode output power of 15 mW were achieved for this device. The 1.5 mm cavity laser had 1425  $\text{\AA}$  pitched gratings and a 937.2 nm free space wavelength. The threshold current and external slope efficiency were 15.2 mA and 0.35 mW/mA per facet. Single mode operation was observed at up to 120 mA (- 36 mW) with a sidemode suppression ration (SMSR) of 30 dB. Above 120 mA Fabry-Perot modes, which can be suppressed by anti-reflection coating the facets, begin to compete with the DFB mode.

The spectral characteristics of the devices were affected by the proximity of the gain peak to the DFB mode. LC-DFB devices with 500  $\mu\text{m}$  and 1 mm cavity lengths displayed a mixture of F-P and DFB modes at room temperature. Shifting the gain peak by cooling or heating the devices allowed both 1400 and 1425  $\text{\AA}$  pitched devices to lase at the Bragg wavelength. Reducing the laser cavity to 250  $\mu\text{m}$  moves the gain peak to shorter wavelengths and resulted in single mode performance for 1400  $\text{\AA}$  pitched DFBs. Single mode performance was also observed for 1.5 mm cavity length LC-DFBs with 1425  $\text{\AA}$  pitched gratings. This is due to a combination of a shift to longer wavelength of the gain peak and an increased  $\kappa L$  (coupling coefficient x cavity length) product. Figure 3 shows the lasing wavelength of 250  $\mu\text{m}$  (1400  $\text{\AA}$  pitch) and 1.5 mm (1425  $\text{\AA}$  pitch) cavity length LC-DFBs along with standard ridge lasers as the heat sink temperature was varied from 5 to 50  $^{\circ}\text{C}$ . The F-P modes (and the gain peak) of the standard ridge lasers shift at a rate of 2.8 (250  $\mu\text{m}$ ) to 3.2 (1.5 mm)  $\text{\AA}/^{\circ}\text{C}$  compared to a much slower rate of 0.63 (250  $\mu\text{m}$ ) to 0.66 (1.5 mm)  $\text{\AA}/^{\circ}\text{C}$  for the LC-DFB devices. This indicates that the lasing wavelength of the LC-DFB is being determined by the gratings and effective refractive index of the mode instead of the bandgap of the quantum well. Below 10  $^{\circ}\text{C}$  and above 45  $^{\circ}\text{C}$  F-P modes began to compete with the Bragg mode in the 1.5 mm cavity DFB.

*Summary and Conclusion:* Single mode distributed feedback laser diodes were produced that rely on the lateral coupling of the evanescent electromagnetic fields with gratings etched along the sides of the ridge. A LC-DFB threshold of 11 mA and slope efficiency of 0.46 mW/mA per facet were achieved for a 250  $\mu\text{m}$  cavity length. A 1.5 mm long device showed single mode DFB behavior up to 36 mW with a SMSR of 30 dB at 937.5 nm. A temperature sensitivity of approximately 0.65  $\text{\AA}/^\circ\text{C}$  was measured for the DFB modes compared to 3  $\text{\AA}/^\circ\text{C}$  for F-P lasers from the same wafer.

Laterally-coupled ridge DFBs formed in this manner eliminate the need for epitaxial regrowth. This allows the complete structure to be grown without interruption resulting in better manufacturability and potentially higher reliability. The gain peak and material quality of the device structure can be determined before the gratings are etched. This technique could be used to fabricate DFBs in material systems for which regrowth is prohibitive - such as high Al concentration (short wavelength and visible lasers) and GaSb (long wavelength) based devices.

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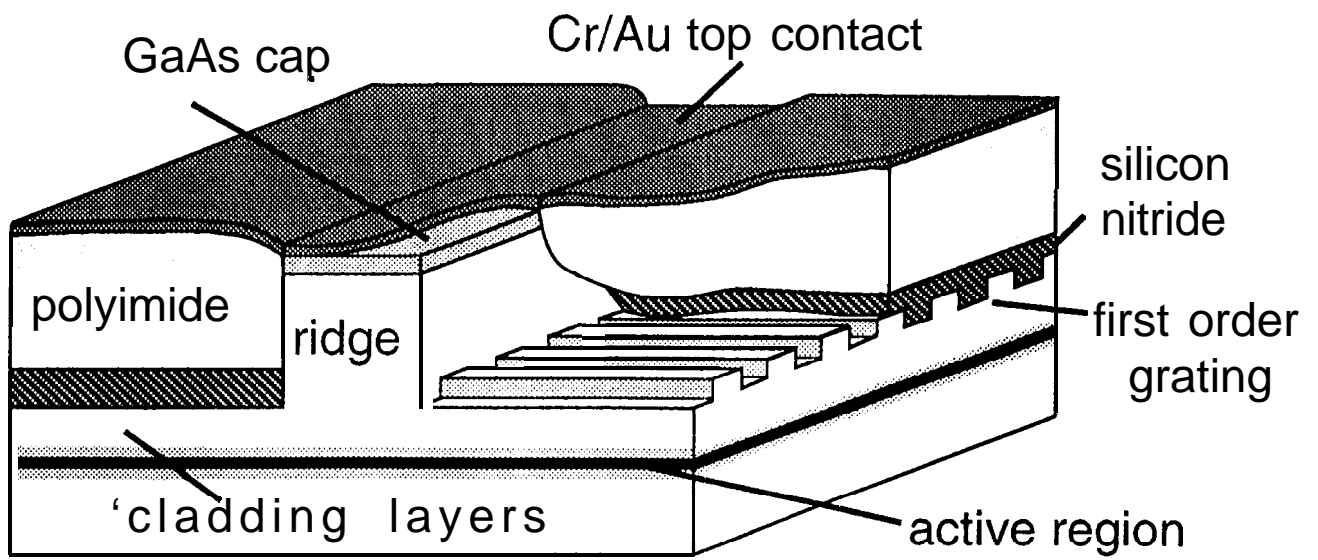
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### Figure Captions:

**Fig. 1** (a) Diagram of a laterally-coupled distributed feedback (LC-DFB) ridge laser diode and (b) SEM photograph of the first order grating pattern defined in PMMA by e-beam lithography.

**Fig. 2** Pulsed light versus current and spectral characteristics of 250  $\mu\text{m}$  and 1.5 mm cavity LC - DFBs. The spectrums shown were taken at 45 mA and 120 mA current injection levels.

**Fig. 3** Lasing wavelength as a function of heat sink temperature for F-P (● 1.5 mm, ◆ 250  $\mu\text{m}$ ) and LC-DFB (○ 1.5 mm - 1425  $\text{\AA}$  pitch, ○ 250  $\mu\text{m}$  - 1400  $\text{\AA}$  pitch) ridge lasers.



(a)



(b)

Figure 1

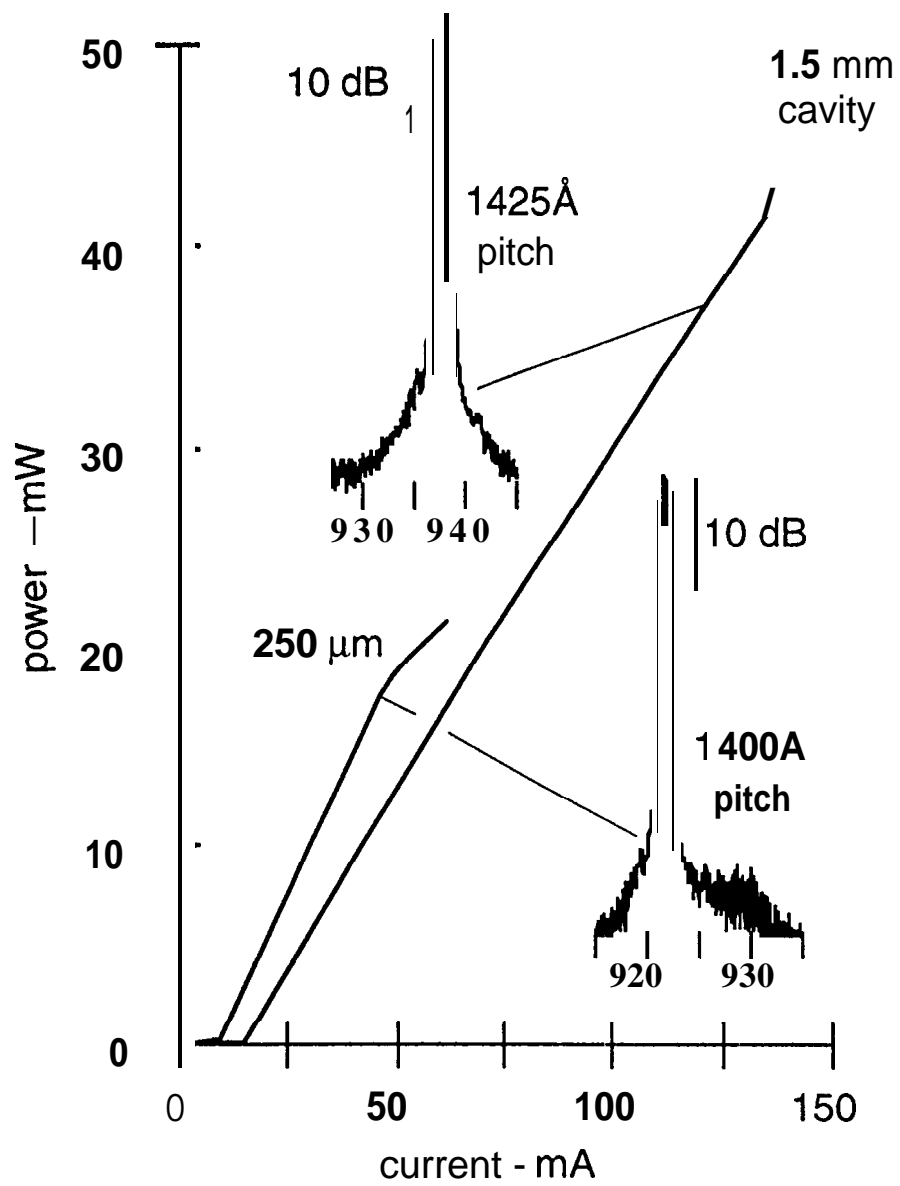


Figure 2

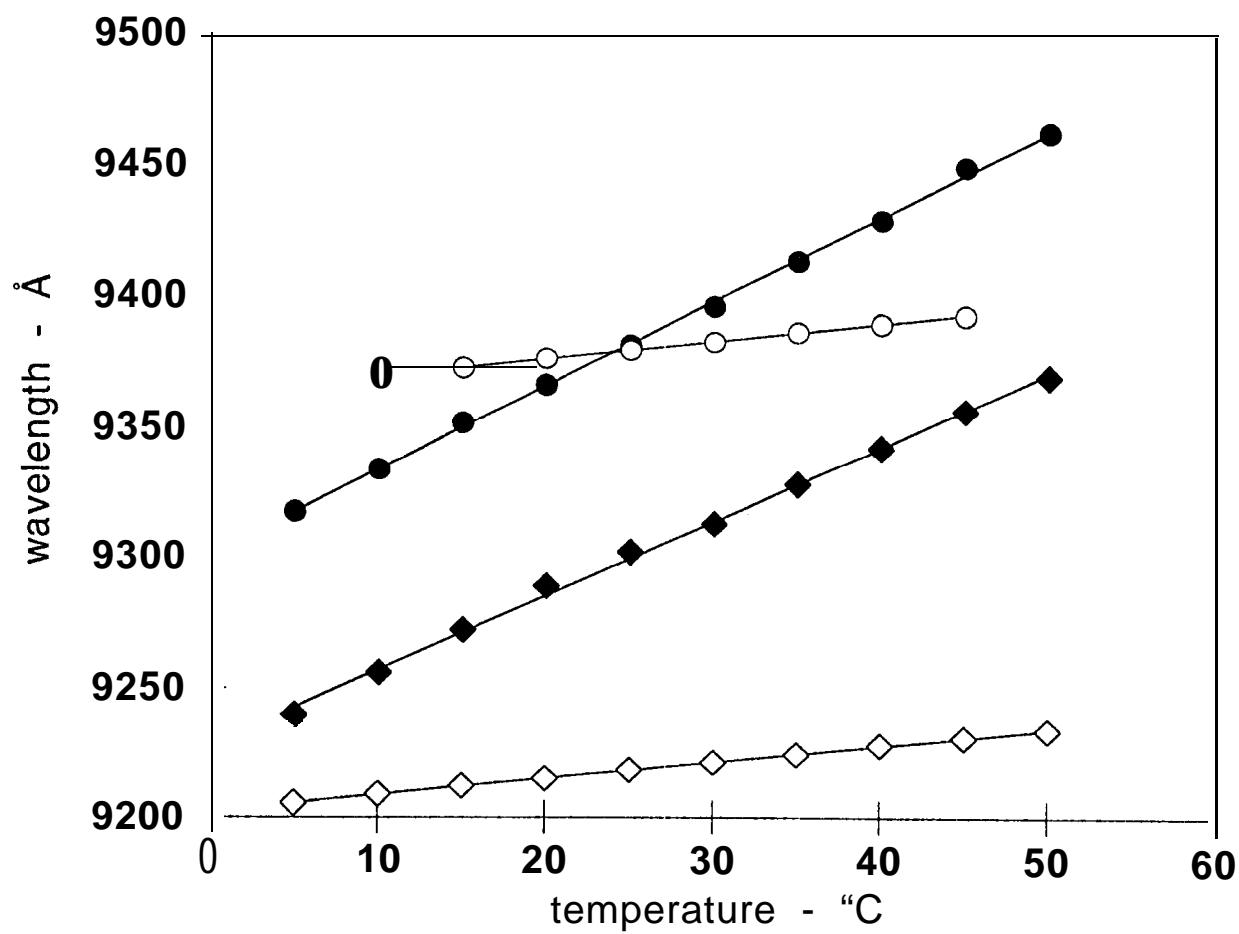


Figure 3